FINAL TECHNICAL REPORT

PALEOSEISMIC INVESTIGATION OF THE SOUTHERN RODGERS CREEK FAULT, MARTINELLI RANCH, SONOMA COUNTY, CA

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ABSTRACT

The Working Group on California Earthquake Probabilities (WGCEP, 2003) evaluated the seismic hazards posed by known active faults in the San Andreas fault system and assigned the greatest probability (27%) for a **M** ≥6.7 earthquake within the next 30 years to the Hayward-Rodgers Creek fault system. One scenario considers the entire rupture of the Rodgers Creek and Hayward faults in an earthquake of **M** 7.3. However, information used to assess slip rate and timing of past earthquakes on the Rodgers Creek fault is based on limited data from only two paleoseismic investigations along the central part of the fault. The distribution of historical seismicity shows a prominent gap in seismicity along the southern Rodgers Creek fault suggesting that this part of the fault may behave independently.

We conducted a feasibility study at Martinelli Ranch in Sonoma County to evaluate possible evidence for latest Holocene surface rupture of the southern Rodgers Creek fault and, if possible, estimate the timing of the most recent earthquake. Through detailed Quaternary geologic and geomorphic mapping we identified three active traces of the Rodgers Creek fault that displace or underlie late Holocene to historic fluvial terraces of Champlin Creek. We documented a hand-excavated test pit and two creek banks that exposed strands of one of the active fault traces. At the site, the fault strike ranges from N19°W to N38°W with moderate to shallow dips between 20°W to 70°W. All documented exposures of the fault show apparent west-side-up vertical separation that we attribute to predominantly right-lateral displacement with a possible minor component of vertical slip. Aseismic creep has not occurred along this fault trace in the latest Holocene because all fault strands and evidence of shearing observed in creek and test pit exposures terminated at unconformities below late Holocene to historic fluvial deposits.

The results of this feasibility study clearly document Holocene surface rupture along the southern Rodgers Creek fault. It is not likely that further excavation at the site will provide significant additional information. Evidence for surface-fault rupture includes multiple low-angle west-dipping fault strands that truncate early Holocene fluvial gravels and terminate below younger, undeformed terrace deposits. The youngest deposit contains fragments of glass attesting to its historic age. We collected detrital charcoal from both the faulted deposits and overlying, undeformed deposits. The results of AMS radiocarbon analyses of these detrital charcoal samples provide age constraints that bracket the most recent earthquake recorded at the site. The broad range in deposit ages indicates that at least one event occurred before 1,050-790 cal yr BP and after 10,730-9,550 cal yr BP.

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1.0 INTRODUCTION

The 60-km-long Rodgers Creek fault, located between San Pablo Bay and Santa Rosa, California, strikes approximately N35°W, and is characterized by a late Holocene right-lateral slip rate of 6.4 to 10.4 mm/yr (Budding et. al, 1991; Schwartz et. al, 1992). The Rodgers Creek fault is one fault in a series of right-stepping en echelon faults that include the Hayward fault to the south, and the Healdsburg and Maacama faults to the north (Figure 1). The surface expression of the Rodgers Creek fault, as mapped by Randolph and Caskey (2001) and Hart (1992), includes classic fault-related geomorphic features such as offset drainages, side hill benches, tonal lineaments, sag ponds, and springs.

The Working Group on California Earthquake Probabilities (WGECP, 2003) defined the Hayward-Rodgers Creek fault system as having the greatest probability (27%) in the San Francisco Bay region of generating an earthquake of **M** 6.7 or greater (where **M** represents moment magnitude). However, data used to develop the probabilities for the Rodgers Creek fault are based on findings from only two studies along the central fault trace (Budding et. al, 1991; Schwartz et. al, 1992). Obtaining additional paleoseismic data from the southern part of the fault is critical to gain a better understanding of the timing of large paleoearthquakes for the Rodgers Creek fault, and for assessing seismic hazards and calculating probabilities of large earthquakes in the rapidly expanding urban area of the northern San Francisco Bay region.

The Hayward-Rodgers Creek fault system is a significant seismic source located in the northern San Francisco Bay area. Most investigators interpret the Rodgers Creek fault as a single fault system capable of generating a **M** 7.1 earthquake, or if it ruptures simultaneously with the northern Hayward fault, a **M** 7.3 earthquake (WGCEP, 2003). Either earthquake likely would severely impact the San Francisco Bay area through surface-fault rupture and strong ground shaking (Association of Bay Area Governments, 1999). During a large-magnitude earthquake on the Rodgers Creek fault, major lifeline systems will be disrupted, including water delivery, levees, transportation, power, and telecommunication systems, and there will be significant damage to critical and non-critical facilities. Currently the Rodgers Creek fault is poorly characterized and we lack the necessary paleoseismic data to assess the potential of a single continuous rupture, or smaller independent rupture segments along the fault system.

To better characterize the southern Rodgers Creek fault, we conducted a feasibility study at Martinelli Ranch in Sonoma County, to evaluate evidence for late Holocene surface rupture and, if possible, estimate the timing of the most recent earthquake. The scope of this study includes (1) detailed mapping of possible late Holocene fault-related geomorphic features and Quaternary geology at the site and (2) evaluating possible stratigraphic and structural evidence for the most recent earthquake on the Rodgers Creek fault. At the study site, the fault crosses late Holocene and historic terraces formed by Champlin Creek near Highway 116 (Figure 3). The site was identified during field reconnaissance and recent detailed mapping along the southern Rodgers Creek fault (Randolph and Caskey, 2001). The tasks completed for this investigation include: (1) field reconnaissance and review of aerial photography; (2) construction of a detailed map depicting Quaternary geology, geomorphology and fault lineaments; (3) topographic surveying; (4) excavation and documentation of two test pits, and two creek bank exposures to evaluate the site stratigraphy; and (5) collection of organic material to be evaluated by radiocarbon analyses.

2.0 GEOLOGIC AND SEISMOTECTONIC SETTING

2.1 Geologic Setting

The Rodgers Creek fault lies within the California Coast Range physiographic province in southern Sonoma County (Figure 1). This region is characterized by north- to northwest-trending mountain ranges and valleys that are oriented sub parallel to the major strike-slip faults of the region.

The study site at Martinelli Ranch is located directly south of and along Highway 116 within the southern Sonoma Mountains (Figure 2). Bedrock mapped in the area includes the Tertiary lower Petaluma Formation and Sonoma Volcanics. Locally, the lower Petaluma Formation occurs west of the active trace of the Rodgers Creek fault, and Tertiary Sonoma Volcanics occur on the east side of the fault. The dominant lithology of the Sonoma Volcanics in this area is rhyolite tuff (Huffman and Armstrong, 1980; Wagner et. al., in press). Exposures of both types of bedrock reveal highly fractured and sheared rock across the total width of the fault zone, which is believed to be approximately 75 m wide in this area.

The test pits and creek exposures investigated by this study are located along Champlin Creek, which is an ephemeral stream locally flowing from southwest to northeast into Sonoma Valley. Multiple late Holocene to historic stream terraces formed by the creek overlie the active fault trace (Figure 3). Two older Holocene terraces offset by the fault provide evidence for surface fault rupture. Our mapping supports previous mapping by Hart (1991) who notes a 5-meter right-lateral deflection in the creek across the fault at the study site. Grazing cattle have had some impact on the topography near the creek, making subtle topographic features difficult to interpret.

2.2 Seismotectonic Setting

The Bay Area is seismically very active and has experienced at least nineteen **M** >6.0 earthquakes during the last 150 years (WGCEP, 2003). Historically, the Rodgers Creek fault has been seismically quiescent. The only moderate to large earthquakes located near the fault were the 1969 **M** 5.6 and 5.7 earthquakes near Santa Rosa (Cloud et. al, 1970; Wong, 1991), and the Mare Island event of 1898 (Figure 4). Based on historical accounts for the region, the 1898 earthquake is interpreted by Toppozada et al. (1992) as a **M** 6.2 to 6.7 event that probably occurred along the southernmost section of the Rodgers Creek fault. However, the location of the 1898 event remains uncertain due to the lack of definitive supporting information.

During the time since the 1906 San Francisco earthquake on the San Andreas fault, the paucity of moderate to large earthquakes suggests that the Bay Area has been in a stress shadow (Harris and Simpson, 1998). Elastic static stress models support a theory in which the 1906 event caused a relaxation of stress on faults of the San Andreas system (Harris and Simpson, 1998). Since the 1989 Loma Prieta earthquake, it is believed that the San Francisco Bay area is emerging from the 1906-induced stress shadow, and that faults that have been quiescent during the past century, may now once again become more seismically active (Simpson and Reasenberg, 1994).

In the San Francisco Bay area, 39 mm/yr of movement is partitioned among the many faults of the San Andreas system (Argus and Gordon, 2001). The San Andreas and San Gregorio faults account for approximately 55% of the 39 mm/yr, and show a combined slip rate of 21mm/yr (Argus and Gordon, 2001). The rates obtained from Global Positioning data are generally in agreement with right-lateral slip rates across the San Andreas fault system determined from geologic data (Prescott et. al., 2001). The East Bay fault system accounts for the remaining 19 mm/yr of strain accumulation (Argus and Gordon, 2001).

The Hayward and Rodgers Creek faults are believed to accommodate 9±2 mm/yr of the East Bay fault system slip rate (WGCEP, 2003).

Strike-slip faults dominate the seismic hazards in the San Francisco Bay area. Although the San Andreas fault exhibits the highest slip rate of all the faults in the Bay area, the WGCEP (2003) concludes that of the Bay area faults, the Rodgers Creek-Hayward fault system has the greatest calculated probability (27%) of producing a M≥6.7 earthquake before 2031. Independent of the Hayward fault, the Rodgers Creek fault is proposed to have a 18% probability of a large event. This is higher than the 13% probability of a large surface rupture for the San Andreas fault calculated over the same time frame. The Rodgers Creek-Hayward fault system is calculated to have the greatest probability for a large event, even though overall this fault system has a lower slip rate than the San Andreas fault (6-10 mm/yr compared to 21-25 mm/yr). This is attributed to the longer amount of time since the last large earthquake on the Rodgers Creek and Hayward faults relative to the San Andreas fault.

Paleoseismic investigations at two sites, Triangle G and Beebe Ranch, provide information on the late Holocene slip rate and event chronology for the central part of the fault (Budding et. al, 1991; Schwartz et. al, 1992). These studies report a geologic slip rate of 6.4 to 10.4 mm/yr along the fault, and an average earthquake recurrence interval of 131-370 years. Schwartz et al. (2001) constrain the timing of the most recent earthquake on the Rodgers Creek fault between A.D. 1640 to A.D. 1776. Trenches at the Triangle G site show evidence for at least two older events within the last ~1,100 years (Schwartz et al., 1992). Although active creep has been documented both south and north of the Rodgers Creek fault along the Hayward and the Maacama faults, respectively, the Rodgers Creek fault does not creep. For example, approximately 10 years of theodolite triangulation data document the absence of surface creep observed along the southern Rodgers Creek fault (Wong, 1991; Galehouse, 1992).

3.0 APPROACH AND METHODS

This study of the Rodgers Creek fault was accomplished by completing five main tasks: (1) field reconnaissance and interpretation of aerial photography; (2) development of a detailed Quaternary geologic and geomorphic map of the site, including locations of active traces of the Rodgers Creek fault, (3) a detailed topographic survey, (4) documentation of four fault-normal excavations that expose late Holocene to historic fluvial deposits; and (5) collection of detrital charcoal and bulk sediment samples for radiocarbon and pollen analyses. The methods used to complete the study are described below.

We developed a detailed Quaternary geologic map for the site that delineates conspicuous late Holocene stream terraces, colluvium, landslides, and local exposures of bedrock that constrain the locations of active fault traces (Figure 5). Active traces of the Rodgers Creek fault depicted on the map (Figures 3 and 5) are based on previous mapping by Hart (1991) and Randolph Loar (2002) and field reconnaissance conducted during this study.

We used a Topcon electronic total station to develop a detailed topographic map of the site (Figure 5) that covers an area approximately 100 m x 160 m. Survey data along Champlin Creek were detailed enough to construct a topographic map with a 0.20 m contour interval.

Two hand-excavated test pits and two natural creek exposures were documented to investigate the stratigraphic and structural relationships across a recently active trace of the Rodgers Creek fault. Test pit T-1, approximately 1 m wide, 3 m long, and up to 1.5 m deep, was excavated southeast of the active creek channel (Figure 5). Creek exposure T-2 was approximately 5 m long and up to 3 m tall. Creek exposure T-3 was 6 m long, and up to approximately 1.25 m high. Test pit T-4, about 1 m wide, 2.25 m long, and 1 m deep, was excavated on terrace Qt_3 adjacent to Highway 116 (Figure 5). After cleaning the exposures, stratigraphic and structural relationships were flagged and logged at a scale of 1 inch = 0.5 meters. Samples collected from the exposures included charcoal for radiocarbon dating and bulk sediment to assess the presence or absence of pollen from historically introduced plant species. Two charcoal samples, one from Qt_2 and one from Qt_3, were submitted to Geochron Laboratories for AMS radiocarbon analyses.

4.0 RESULTS

The results of this investigation indicate that Holocene deposits of Champlin Creek preserve evidence for at least one earthquake along southern Rodgers Creek fault. We identified four terrace surfaces underlain by late Holocene to historic alluvial deposits, and a buried early Holocene terrace exposed in the bank of Champlin Creek (Figure 5). The youngest terrace deposits are interpreted to be historic in age based on the presence of glass and other cultural debris, their relatively low topographic position, and lack of significant soil development. The fluvial deposits that underlie these historic terraces are undeformed and post-date the most recent event on the fault. Based on stratigraphic and structural relationships documented in test pit and creek exposures (Photo 1), fault displacement of early Holocene alluvial deposits records at least one event that ruptured the surface in Holocene time.

The following sections summarize the results of (1) detailed geologic and geomorphic mapping at the Martinelli Ranch site, (2) stratigraphic relationships documented in test pits and creek exposures investigated along an active fault trace, (3) radiocarbon analyses of detrital charcoal, and (4) structural relationships that indicate Holocene surface fault rupture on the southern Rodgers Creek fault. A detailed geologic and geomorphic site map is presented on Figure 5. Stratigraphic and structural relationships encountered in the excavations are depicted in Figures 6 through 9. Finally, detailed geologic unit descriptions are included in Appendix A.

4.1 Quaternary Geologic and Geomorphic Mapping

Through interpretation of 1:6,000-scale aerial photography flown in 1991 and field reconnaissance, we characterized the geomorphic expression of active traces of the Rodgers Creek fault at the Martinelli Ranch site (Figure 3). Three main fault traces cross the study site and are strongly expressed in the topography as vegetation and tonal lineaments, linear drainages, slope breaks and right-lateral deflection of Champlin Creek. Southeast of the study site, the two active traces on the west bound a closed depression (cd, Figure 3) that may indicate slight transpressive deformation within the fault zone. The eastern and central active traces are coincident with conspicuous right-lateral offsets along the trend of the active channel of Champlin Creek (od, Figure 3). The strong geomorphic expression of these faults helped guide the location of test pits and creek exposures investigated in this study. The fault traces are interpreted as active because creek bank and test pit exposures across the faults show offset Quaternary colluvial and alluvial deposits that, in some places, are juxtaposed against bedrock. Secondary faults or possibly non-tectonic lineaments parallel the active fault traces directly east and west of the study site (Figure 3). The geomorphic features that characterize the secondary faults include distinct to weakly pronounced vegetation and tonal lineaments, linear ridges and troughs (Figure 3).

Detailed Quaternary geologic mapping of the study site identified four late Holocene to historic fluvial terraces and two latest Pleistocene to early Holocene terraces along the margins of Champlin Creek (Figure 5). The youngest fluvial terraces (Qt_4, Qt_5 and Qt_6) that overlie active fault traces are undeformed and are interpreted to be historic in age due to the presence of cultural debris, including glass and nails, in the deposits underlying the terraces. Terrace deposits of Qt_3, also undeformed above the fault, range from 1,050 to 790 cal yr BP based on AMS analysis of detrital charcoal (Table 1). Active strands of the Rodgers Creek fault offset older fluvial terraces (Qt_1 and Qt_2) that were deposited in the latest Pleistocene to early Holocene, based on a single age from detrital charcoal in Qt_2 (Table 1). Other Quaternary geologic units identified on the map include active stream channel deposits, late Holocene landslide deposits, and Holocene colluvium (Figure 5). Local bedrock outcrops, including the Tertiary lower Petaluma Formation and Sonoma Volcanics, also are depicted on the map, especially along the active fault traces. A survey of the basal strath surfaces beneath some of the mapped terraces confirmed the correlation between the fluvial deposits documented in creek and test pit exposures and the terraces identified by surficial mapping (Figure 5).

Table 1. Results of Radiocarbon Analyses on Detrital Charcoal Samples

Lab Number[a]	Sample Code	Material Dated	$\delta^{13}C$ (‰)	Lab-reported age (^{14}C yr BP, 1σ)[b]	Calibrated age (cal yr BP, 2σ)[c]
GX31031	RC-T3-1	Charcoal	-27.5	1000+/-50	1,050-790
GX31032	RC-T3-2	Charcoal	-25.4	9,070+/-210	10,730-9,550

[a]Samples analyzed by Geochron Laboratories, Cambridge, MA
[b]Date determined by accelerator mass spectrometry, based on Libby half life (5570 yrs) and referenced to A.D. 1950.
[c]Calibrated age ranges calculated using Calib v. 4.4.2 (Stuiver and Reimer, 1993; Stuiver et al., 1998).

4.2 Stratigraphic Relationships

Bedrock encountered in the test pits and creek exposures include the Tertiary lower Petaluma Formation and Sonoma Volcanics. Locally, the lower Petaluma Formation is characterized as dominantly shale with interfingering beds of moderately to well consolidated mudstone (Tlp_m), and sandstone (Tlp_s). The Sonoma Volcanics are a heterogeneous assemblage of lava and pyroclastic tuff that range from basaltic to rhyolitic compositions. Typical Sonoma Volanics bedrock mapped on the Martinelli site include andesite (Tsv_a) and rhyolitic tuff (Tsv_r; Wagner et. al., in review). In test pit T-1 (Photo 2, Figure 6), pervasively sheared zones of bedrock that include alternating slivers of Sonoma Volcanics rhyolite tuff and lower Petaluma mudstone are depicted as Tpl/Tsv.

Two remnant slivers of probable pre-Quaternary alluvial deposits (Tsg? and QTg?) occur in test pit T-1 (Photo 2, Figure 6). Unit Tsg? consists of yellowish brown sandy gravel derived exclusively from Sonoma Volcanics bedrock and is limited to a fault bound wedge, which is juxtaposed against lower Petaluma Formation mudstone on the west and Sonoma Volcanics on the east (Figure 6). Unit QTg? consists of dark reddish brown gravelly clay also derived solely from the Sonoma Volcanics. Also bound by active strands of the Rodgers Creek fault, QTg? occurs as a thin, wedge-shaped sliver within the fault zone exposed in test pit T-1 (Figure 6).

Natural creek exposures (T-2 and T-3, Photos 3 and 4, respectively) are cut into alluvial deposits associated with six stream terraces, identified from oldest to youngest as Qt_1 through Qt_6 (Figures 7 and 8). Creek exposure T-2 contains the gravels associated with the oldest alluvial deposits identified at the site (Qt_{1a} and Qt_{1b}; Figure 7). These deposits overlie a strath terrace cut into Sonoma Volcanics bedrock (Figure 7), and show a general fining upward trend with cobbles and boulders at the base up to 0.5 m in diameter. Although the unit was generally massive, some lenticular gravel beds were observed. We interpret that the gravels that underlie the Qt_1 terrace were deposited in the latest Pleistocene to early Holocene based on the age of detrital charcoal from Qt_2 deposits. The higher topographic position of Qt_1 implies that Qt_2 is inset into Qt_1 and therefore younger. Aggrading Champlin Creek channel deposits of Qt_3, Qt_4, Qt_5, and Qt_6 subsequently buried Qt_2. Detrital charcoal samples collected from Qt_1 gravel deposits potentially could provide direct radiocarbon age estimates for the terrace. However, we did not submit any of these samples due to budgetary constraints and the priority to date other samples that directly bracket stratigraphic evidence of the most recent event recorded at the site.

A package of alluvial deposits that includes Qt_{2a}, Qt_{2b}, Qt_{2c} and Qt_{2d} underlies a buried Holocene terrace designated as Qt_2 (Figure 8). These deposits consist of yellowish to reddish brown, moderately consolidated gravels and clayey gravels that fine upward to gravelly sand. Deposits of Qt_2 are faulted against lower Petaluma Formation mudstone and Sonoma Volcanic rocks on the west (Figure 8). The oldest deposit in this package exhibits slight reddening and thin clay films on the base of a few gravel clasts. AMS radiocarbon analysis of detrital charcoal sampled from the deposits (Figure 8) indicates a latest Pleistocene to early Holocene age of 10,730 to 9,550 cal yr BP (Table 1).

Four younger alluvial terraces and associated sediments (Qt_3, Qt_4, Qt_5 and Qt_6) that flank Champlin Creek overlie active traces of the Rodgers Creek fault and are undeformed (Figure 5). Alluvium underlying terrace Qt_3 includes five fining upward deposits of gravel and gravelly silt (Qt_{3a} through Qt_{3e}; Figure 8). These deposits are generally gray to dark gray in color, less consolidated than underlying gravels and show little to no soil development. These characteristics of the deposits, and the relatively low topographic relief of the terraces, support the interpretation that younger undeformed alluvium was deposited in the latest Holocene or historically. Support for this interpretation comes from the results of radiocarbon analysis of detrital charcoal from Qt_{3b} (Figure 8) that provide an age of 1,050 to 790 cal yr BP (Table 1). On the east side of the exposure (Figure 8) Qt_3 conformably overlies Qt_2; whereas, in the central part of the exposure, Qt_3 overlies a faulted strath surface cut into sheared bedrock. Terrace Qt_4 is mapped downstream of the documented creek exposures (Figure 5) and was not encountered in any of the excavations. Poorly consolidated gravels and silts underlying Qt_5 and Qt_6 contain glass and other cultural debris that attest to their historic ages (Photo 5). These deposits include Qt_{5a}, Qt_{5b}, Qt_{5c} and Qt_6 (Figure 8).

Several small colluvial packages (Qc_4, Qc_3, Qc_2, and Qc_1) are depicted above slivered bedrock units in test pit T-1 (Figure 6). These packages appear to be dominantly derived from the bedrock materials that immediately underlie the deposits. The largest colluvial deposit (Qc_4) is derived from Petaluma Formation bedrock (Figure 6). We interpret this as a proximal scarp-derived colluvial wedge that records surface rupture on the Rodgers Creek fault. No datable material was available to determine the age of this deposit.

Modern soil A-horizons (S_1, S_2 and S_3) developed into thin colluvial deposits and the youngest terrace sediments were mapped in each exposure (Figures 6 through 9). A vertisol (S_1) developed in thin colluvial deposits that mantle faulted bedrock exposed in test pit T-1, thickens slightly on the east side of the active fault zone (Figure 6). Multiple large desiccation cracks up to 1 m deep and other evidence of vertical mixing of the soil profile, imply that shrink-swell processes are active at this locality.

4.3 Radiocarbon Analyses

Small detrital charcoal samples were collected from units Qt_{2b} and Qt_{3b} in exposure T-3 (Figure 8) and from Units Qt_{1a} and Qt_{1b} from exposure T-2 (Figure 7). We submitted two charcoal samples, one from unit Qt_{2b} and one from unit Qt_{3b}, for AMS radiocarbon analyses to estimate the time of surface faulting recorded at the site. Radiocarbon analysis of charcoal from unit Qt_{2b}, which is deformed by the fault, provides a maximum limiting age estimate. Radiocarbon analysis of charcoal from unit Qt_{3b}, which overlies the fault and is undeformed, provides a minimum limiting age estimate. The results of these radiocarbon analyses (Table 1) yield a latest Pleistocene to early Holocene age of 10,730 to 9,550 cal yr BP for unit Qt_{2b}. A latest Holocene age (1,050 to 790 cal yr BP) was determined for detrital charcoal from unit Qt_{3b} (Table 1).

4.4 Structural Relationships

An active trace of the Rodgers Creek fault zone was encountered in test pit T-1 and both creek exposures (T-2 and T-3). The strike of the fault in the trenches ranged from N19°W to N38°W, and fault dips ranged from 22° to 70° to the west. Based on fault attitudes obtained from creek and test pit exposures and on the presence of undeformed alluvium in T-4, the active fault trace underlies the active channel of Champlin Creek northwest of T-3 (Photo 1). Although the fault exhibits an apparent west-side-up sense of vertical separation where observed, we infer that the deformation style is dominantly right-lateral strike-slip because stratigraphic units cannot be correlated across the fault. The following section briefly presents the pertinent structural evidence for at least two earthquakes on the southern Rodgers Creek fault that displaced early Holocene fluvial deposits.

4.4.1 Test Pit T-1

Test pit T-1 exposed multiple fault traces within a shear zone approximately 0.5 m wide (Photo 2). Cross cutting relationships among faulted colluvial strata and bedrock record at least two surface faulting events (Figure 6). However, a lack of chronostratigraphic data in this exposure precludes the estimation of event timing. The average orientation of the fault in bedrock measured across the trench is N21°W, 53°SW. In the lower two-thirds of test pit T-1, the fault zone juxtaposes lower Petaluma Formation on the west against Sonoma Volcanics on the east. Evidence for complex faulting in bedrock includes pervasively sheared rock and bedrock slivers of alternating lithologies of Petaluma Formation mudstone and rhyolite tuff of the Sonoma Volcanics. The origin and age of two fault-bound slivers of sedimentary rock, units Tsg? and QTg? (Figure 6), are unknown and do not provide data useful for interpreting event timing.

Evidence for at least two surface rupturing earthquakes includes cross-cutting relationships between the lower Petaluma Formation, unit QTg?, and an interpreted colluvial wedge (Qc_4) (Figure 6). The earlier event is recorded by offset of the lower Petaluma Formation against unit Tsg? along the western-most fault strand and the subsequent development of an inferred scarp-derived colluvial wedge shown as unit Qc_4 (Figure 6). The apparent west-side-up sense of movement along the fault may record vertical separation caused by predominantly strike-slip displacement with perhaps a minor component of vertical slip.

Evidence for the most recent earthquake at the Martinelli Ranch on the Rodgers Creek fault recorded in test pit T-1 includes displacement of the interpreted colluvial wedge, unit Qc_4 (Figure 6). This event occurred on the eastern-most active fault strand in the trench (Figure 6). This fault places unit QTg? over unit Qc_4 and can be traced to within 20 to 25 cm of the ground surface at the base of unit S_1. We interpret the apparent vertical separation along the fault to be a product of predominantly right-lateral coseismic slip, although we found no kinematic indicators to support this conjecture. Thickening of unit S_1 to the east of the fault suggests the possibility that the most recent event produced a surface scarp that subsequently degraded to form a colluvial wedge. However, if a colluvial wedge formed following the most recent event, the expansive clay rich soil (vertisol) depicted as unit S_1 has since obliterated any stratigraphic evidence of it. Nonetheless, we interpret the eastward thickening of unit S_1 as corroborative evidence for the most recent event in test pit T-1.

None of the fault strands deform the surface soil. We observed no incipient fractures, aligned soil cracks, or fault strands continuing upward into unit S_1. Thus, based on the absence of evidence for deformation of the soil, we interpret that the Rodgers Creek fault has not released strain via aseismic creep at this site since the surface faulting event the displaced unit Qc_4.

4.4.2 Creek Exposure T-2

In creek exposure T-2 (Figure 7), a sliver of the Tertiary lower Petaluma Formation is faulted against and overlies late Holocene alluvial gravels of terrace Qt_1 (Photo 3). The average strike and dip of the fault in this exposure is N6°E, 23°N. In an adjacent creek bank west of the exposure documented in Figure 7, the fault juxtaposes lower Petaluma Formation on the west against Sonoma Volcanics on the east. This relationship, along with the structural characteristics of the fault, including its northwestward strike, southwestward dip and apparent west-side-up vertical separation, is very similar to the structure and style of faulting observed in exposures T-1 and T-3 and leads to the interpretation that the same active fault is encountered in all three exposures (Figures 6, 7 and 8). We interpret that the fault exposed in creek bank T-2 moved in the Holocene based on displacement of alluvium underlying terrace Qt_1, but we lack stratigraphic information and necessary age data to evaluate the event chronology on this trace of the fault. Detrital charcoal collected below the fault in unit Qt_1 deposits could potentially provide radiocarbon ages that would yield maximum limiting age estimates for the time of faulting.

Faulting documented within the rhyolitic unit of the Sonoma Volcanics is restricted to bedrock and did not displace the strath terrace or overlying gravels of Qt_1 (Figure 7).

4.4.3 Creek Exposure T-3

We cleaned and documented a natural exposure (T-3) of the fault in the northeastern bank of Champlin Creek that records geologic evidence for at least one—possibly the most recent—earthquake on the southern Rodgers Creek fault at the Martinelli Ranch (Photo 4). In this exposure, the apparent vertical separation on the fault juxtaposes slivers of the Tertiary bedrock of the lower Petaluma Formation and Sonoma Volcanics over alluvial gravels associated with a buried early Holocene fluvial terrace (unit Qt_2; Figure 8). The average strike and dip of the fault measured in bedrock is N36°W, 40°SW. Beneath the historic terraces (Qt_5 and Qt_6) the lower Petaluma Formation is highly sheared, with an average shear fabric orientation of N38°W, 51°SW.

We interpret evidence for at least one faulting event preserved in creek exposure T-3 to record Holocene surface fault rupture on the southern Rodgers Creek fault. Buried early Holocene gravel deposits of terrace Qt_2 (10,730 to 9,550 cal yr BP; Table 1) are faulted against Tertiary bedrock to the southwest (Figure 8). The fault strands terminate upward at an unconformity below undisrupted Qt_3 terrace deposits that range in age from 1,050 to 790 cal yr BP (Figure 8). Such broad age constraints for the time of faulting (before 1,050 to 790 cal yr BP and after 10,730 to 9,550 cal yr BP) preclude an evaluation of whether stratigraphic and structural relations record the most recent earthquake on the southern Rodgers Creek fault or a prior Holocene event. It is possible that surface fault rupture on the southwestern-most strand exposed in T-3 post dates deposits of Qt_3. If so, any geologic evidence of the event has been eroded by fluvial processes that deposited sediments of Qt_5.

The absence of evidence for deformation of deposits associated with terraces Qt_3, Qt_5, and Qt_6 that overlie the fault zone rules out creep as a mechanism for releasing strain on the Rodgers Creek fault during latest Holocene to historic time.

4.4.4 Test Pit T-4

Alluvial deposits that underlie Qt3 exposed in test pit T-4 are not faulted. Based on the location of test pit T-4 and the absence of evidence of deformation, we conclude that the active trace of the Rodgers Creek fault, observed in exposures T-1, T-2 and T-3, underlies the active channel of Champlin Creek directly west of test pit T-4.

5.0 SUMMARY OF FINDINGS

Proposed as a feasibility study, an initial investigation was performed at the Martinelli Ranch site to evaluate the timing of the most recent event on the southern Rodgers Creek fault, and to identify if the site or proximal sites would yield further information on the late Holocene earthquake history. Geologic mapping and paleoseismic investigations of test pits and natural creek exposures conducted at the Martinelli Ranch site provide new information about the location of the southern Rodgers Creek fault, the style of deformation and broad age constraints on the timing of Holocene surface-fault rupture. The results of this preliminary survey indicate that further excavation at the site likely will not generate significantly more additional information on the history of Holocene earthquakes, with one exception. It is possible that additional AMS analyses of detrital charcoal from faulted fluvial deposits in creek exposure T-2 will provide age estimates to better constrain the timing of Holocene earthquake recorded at the site.

Detailed Quaternary geomorphic and geologic mapping identified three active fault traces crossing late Holocene and historically deposited fluvial deposits along Champlin Creek at the Martinelli Ranch site. Five late Holocene to historic fluvial terraces and a sixth buried terrace were delineated through detailed mapping (Figure 5). Multiple strath surfaces at varying elevations were identified along Champlin Creek and have been interpreted to relate to four of the mapped terrace surfaces (Qt_1, Qt_2, Qt_3, and Qt_5). Elevations of the strath surfaces were surveyed, and support this interpretation of the relative ages between the terraces (Figure 5). Quaternary colluvium dominantly consists of weathered bedrock mantling the lower Petaluma Formation and Sonoma Volcanic units. Landslides also were relatively common in the area, with many of the failures occurring along the southern margin of Champlin Creek.

Two test pits and two stream cutbanks were documented to evaluate the late Holocene activity of one of the active traces identified at the Martinelli Ranch site. As shown in detailed logs of test pit T-1 (Figure 6) and creek exposures T-2 and T-3 (Figures 7 and 8), the fault displaces early Holocene fluvial terrace deposits, thus demonstrating its recent activity. Because fault strands were not observed in test pit T-4, we infer that the active trace lies beneath the creek channel immediately west of this excavation (Figure 5). Where exposed, the fault strike ranges from N19°W to N38°W with shallow to moderate dips ranging from 20°W to 70°W. All exposures of the fault showed apparent west-side-up vertical separation that we attribute to predominantly right-lateral displacement and possibly a minor vertical component of slip that placed Petaluma Formation bedrock on the west against Sonoma Volcanics on the east. We infer that aseismic creep has not relieved strain on the fault trace in the latest Holocene because none of the fault exposures showed fault strands or evidence of shearing that reaches the ground surface.

Evidence for at least one Holocene surface rupture on the southern Rodgers Creek fault is recorded in test pit and creek exposures documented at the site (Figures 6, 7 and 8). In test pit T-1, fault displacement of an interpreted scarp-derived colluvial wedge provides evidence for two earthquakes, yet extensive mixing caused by expansive clay in the shallow colluvial soil and a lack of datable material precludes an assessment of event timing. In exposure T-2, a sliver of Tertiary lower Petaluma Formation is juxtaposed against late Holocene fluvial deposits of unit Qt_1 along a low-angle fault splay that strikes N6°E and dips 23°N. The strongest evidence for Holocene surface-fault rupture is recorded in exposure T-3 (Figure 8). In this natural creek bank exposure we observed multiple low- to moderate-angle fault strands that offset Tertiary Sonoma Volcanics and Petaluma Formation bedrock on the west against early Holocene fluvial gravels of unit Qt_2 on the east. All fault strands terminate at unconformities below younger fluvial deposits of units Qt_3 and Qt_5, the latter that contained fragments of glass attesting to its historic age.

The results of AMS radiocarbon analyses of detrital charcoal from units Qt_{2b} and Qt_{3b} (Table 1; Figure 8) provide age estimates that broadly constrain the time of faulting to before 1,050 to 790 cal yr BP and after

10,730 to 9,550 cal yr BP . Although fault movement recorded in exposure T-3 may represent the most recent event at the site, it is possible that evidence for more recent earthquakes has been erased due to historic fluvial incision by Champlin Creek as evidenced by basal unconformities below Qt_5 and Qt_6.

6.0 NON-TECHNICAL SUMMARY

This research provides information on timing of past large earthquakes along the southern Rodgers Creek fault in northern California. There have been no historic major earthquakes documented on the fault, with existing paleoseismic evidence indicating that the most recent event may have occurred approximately 230 years ago (Budding et. al, 1991). The timing and recurrence of earthquakes along the Rodgers Creek fault is a critical issue for determining seismic hazard in northern California. This paleoseismic study provides additional information that can be used to evaluate the probabilities of strong ground motions and other earthquake-related hazards in northern California. Geologic exposures at the site record evidence for an earthquake on the southern Rodgers Creek fault that occurred between 1,000 to 10,000 years ago.

7.0 ACKNOWLEDGMENTS

This research was supported by a grant to William Lettis & Associates, Inc. from the U.S. Geological Survey (Award number 03HQGR0083). We are especially grateful to the Martinelli family who allowed us to work on their property. J. Thornburg and S. Sundermann assisted with field work.

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FIGURES AND PHOTOS

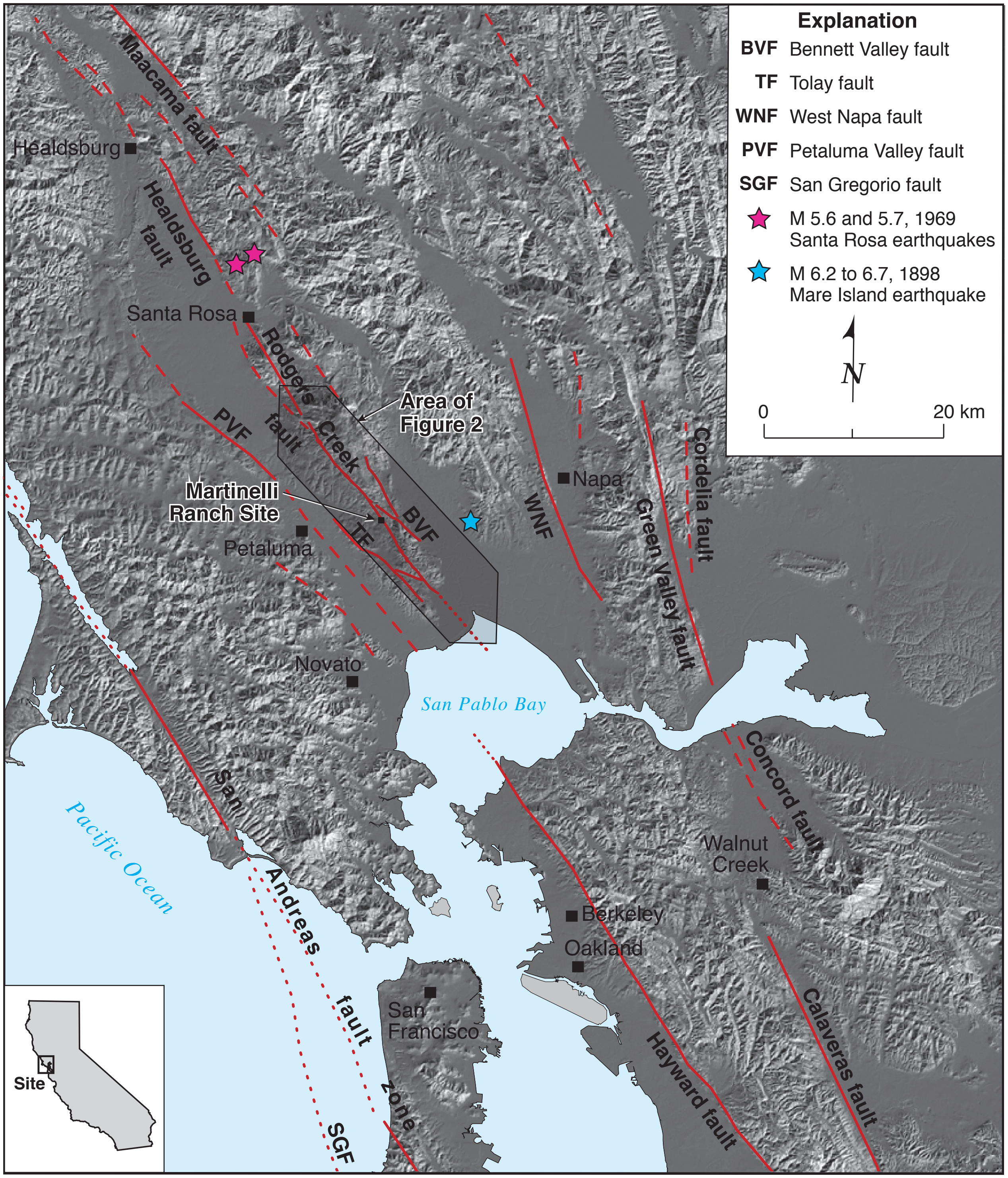


Figure 1. Regional shaded relief map showing the Martinelli Ranch study site, faults modified from Jennings (1994), and the historic earthquakes of 1969 and 1898.

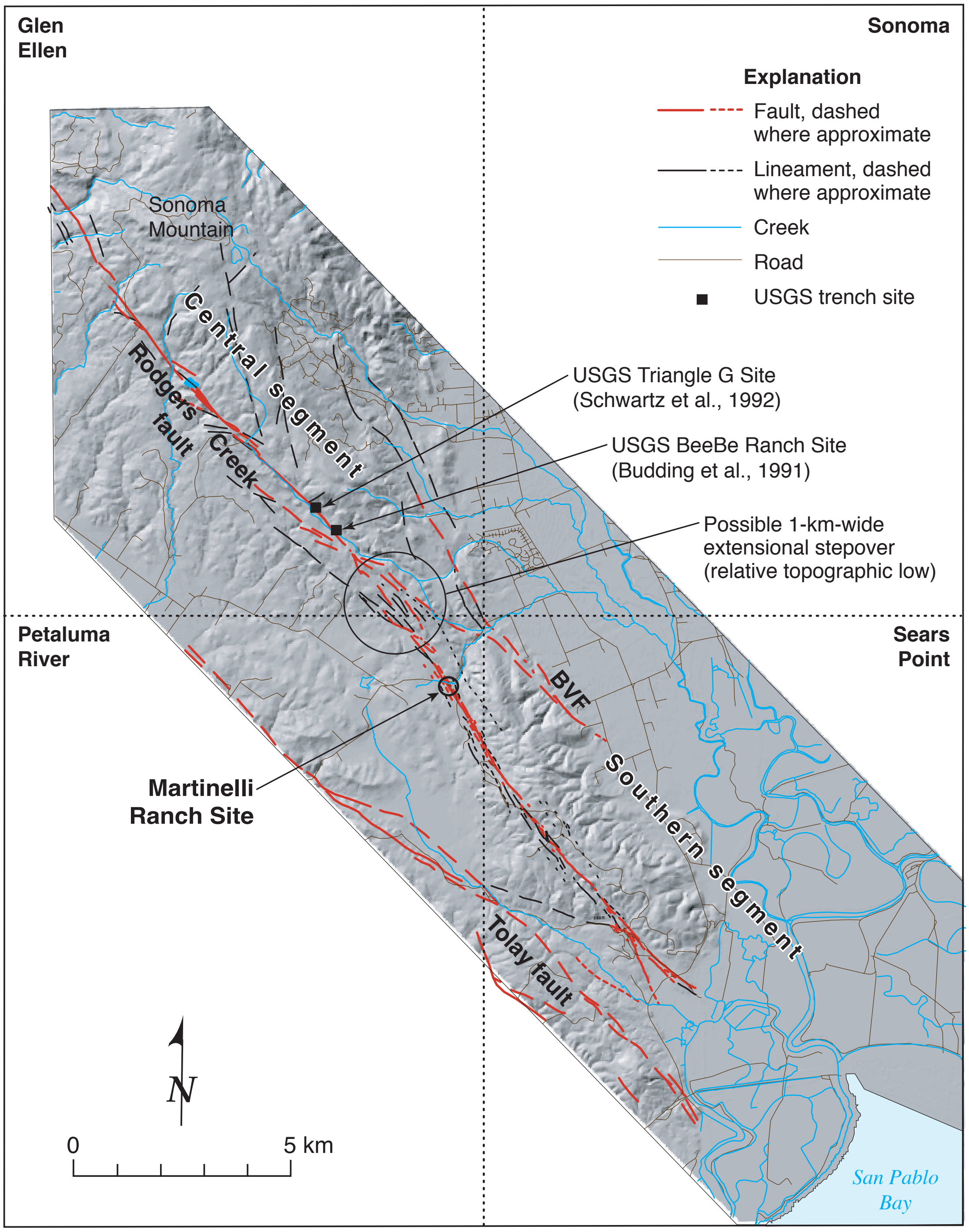


Figure 2. Southern 25 km of the Rodgers Creek fault showing fault and lineament mapping (Randolph and Caskey, 2001) and previous successful paleoseismic investigations on the fault. USGS 7.5-minute Quadrangle boundaries shown by dotted line. Martinelli Ranch study site is located near center of the map, along Champlin Creek and Highway 116.

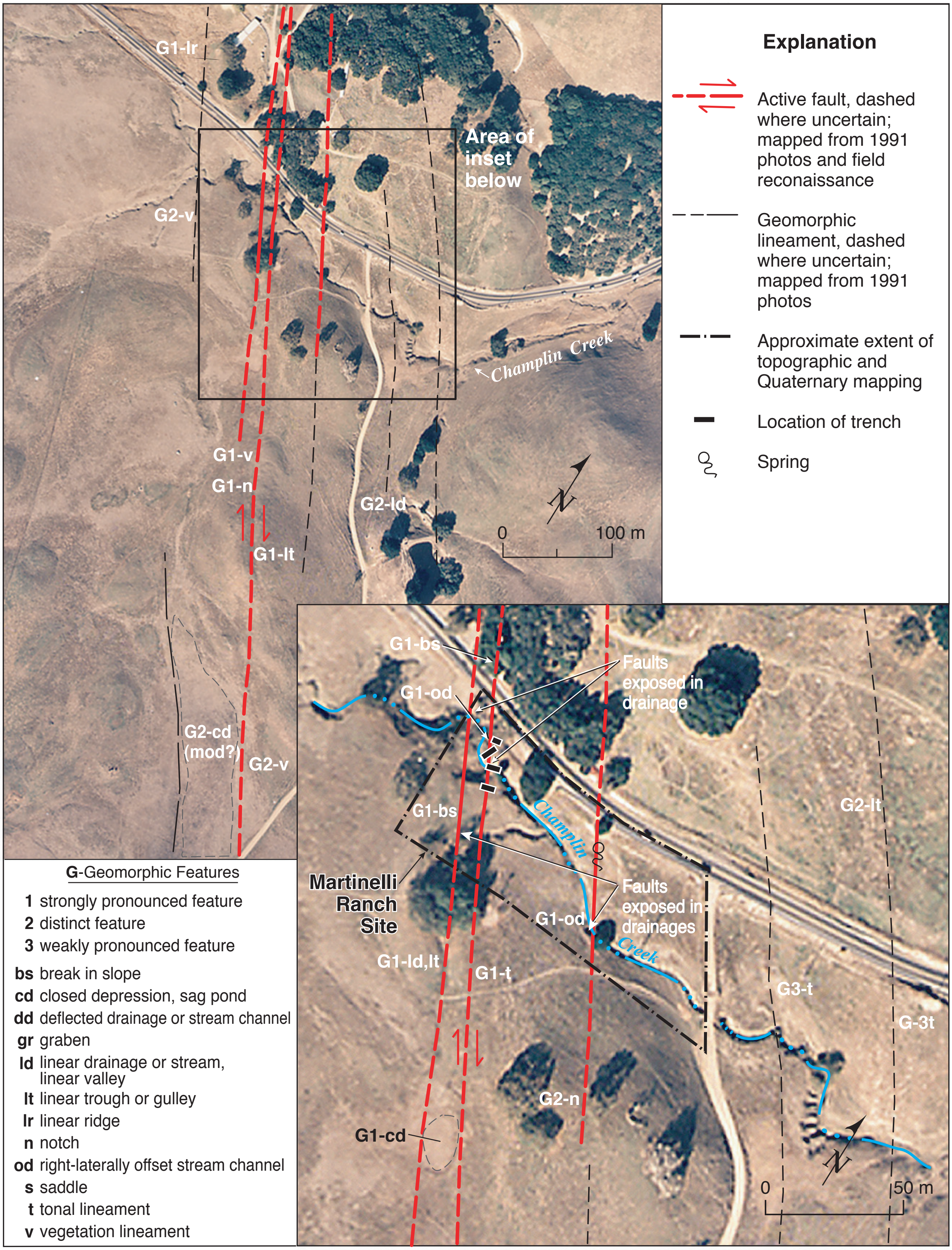


Figure 3. Aerial photograph (1991) of the Martinelli Ranch site showing interpreted active fault traces and fault-related geomorphic features. Inset shows detailed geomorphic expression of active fault traces and the locations of creek and test pit exposures across the central fault trace investigated by this study.

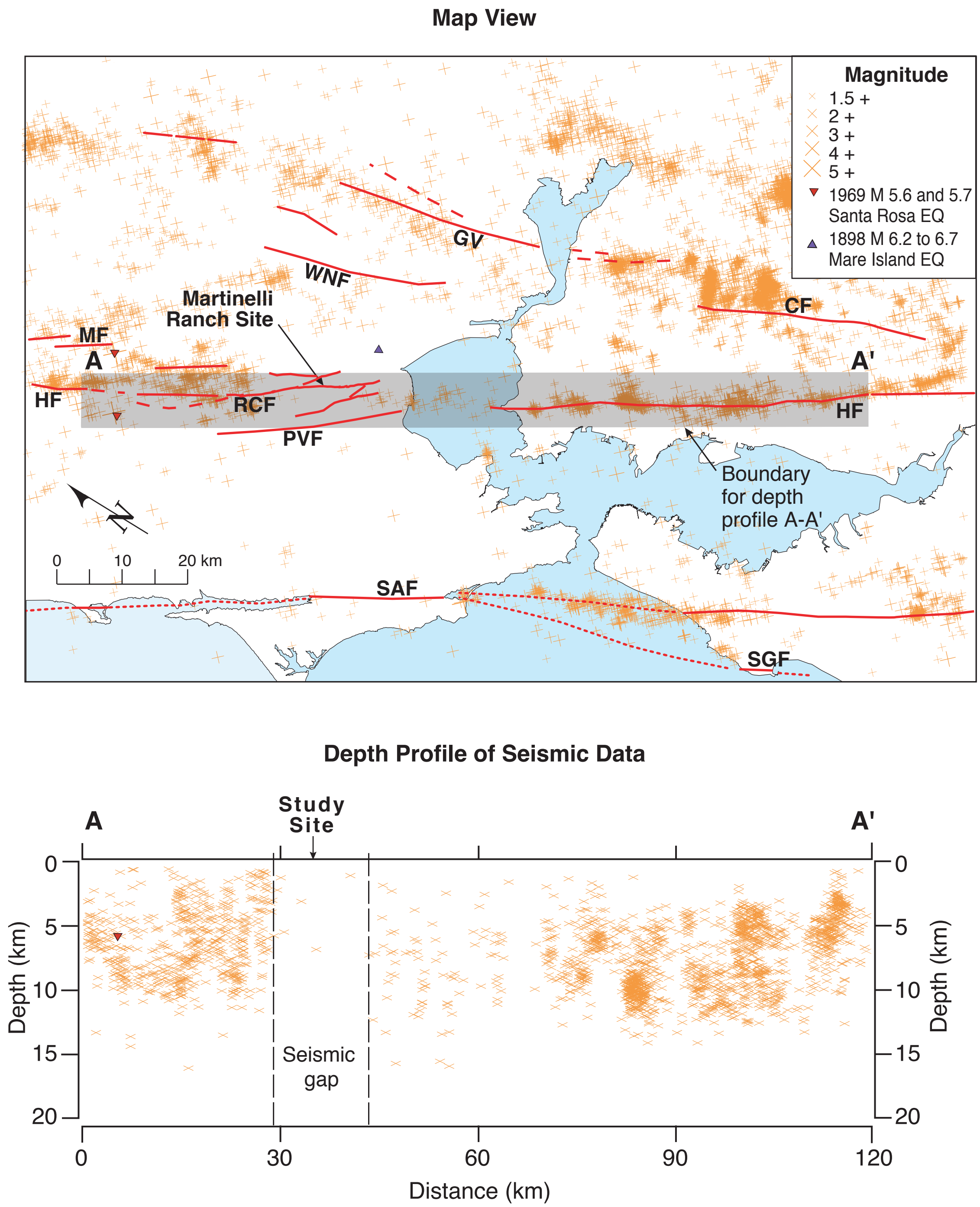
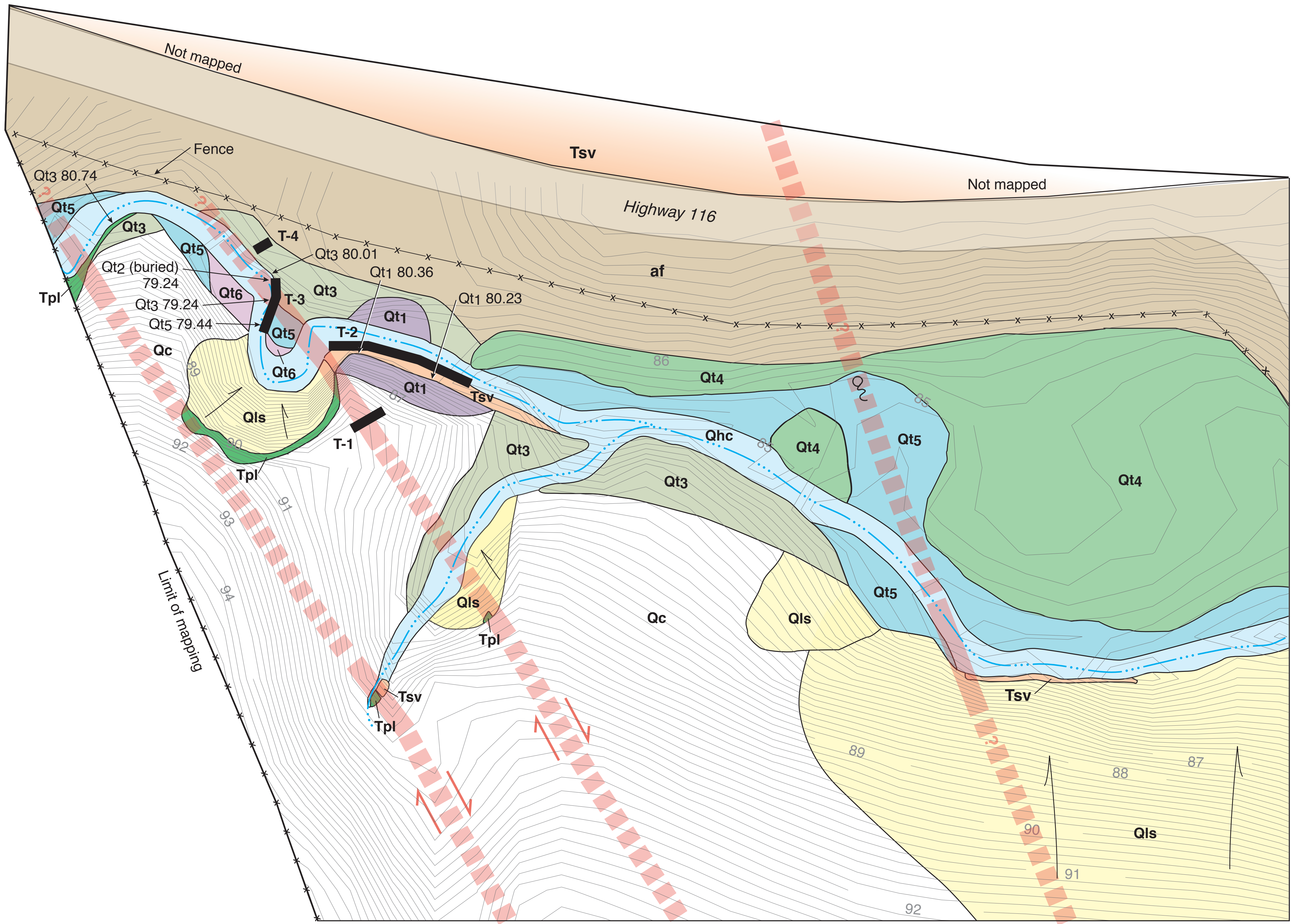


Figure 4. Seismicity data and depth profile along the Hayward-Rodgers Creek faults, showing seismic gap along the southern Rodgers Creek fault. Earthquake data from 1967 to 2002 from the USGS Northern California Seismic Network database (M>1.5) . GV = Green Valley fault, CF = Calaveras fault, MF = Maacama fault, HF = Healdsburg fault, RCF = Rodgers Creek fault, HF = Hayward fault, PVF = Petaluma Valley fault, SAF = San Andreas fault, SGF = San Gregorio fault, WNF = West Napa fault.



Explanation

Unit Descriptions

- Qhc — Active stream channel
- Qt6 — Historic point bar deposits
- Qt5 — Historic stream terrace
- Qt4 — Latest Holocene to historic stream terrace
- Qt3 — Latest Holocene to historic stream terrace
- Qt2 — Buried late Holocene fluvial deposits (not shown)
- Qt1 — Late Holocene stream terrace
- Qls — Late Holocene landslide deposits
- Qc — Holocene colluvium

Bedrock Unit Descriptions

- Tsv — Tertiary Sonoma Volcanics
- Tpl — Tertiary lower Petaluma Formation

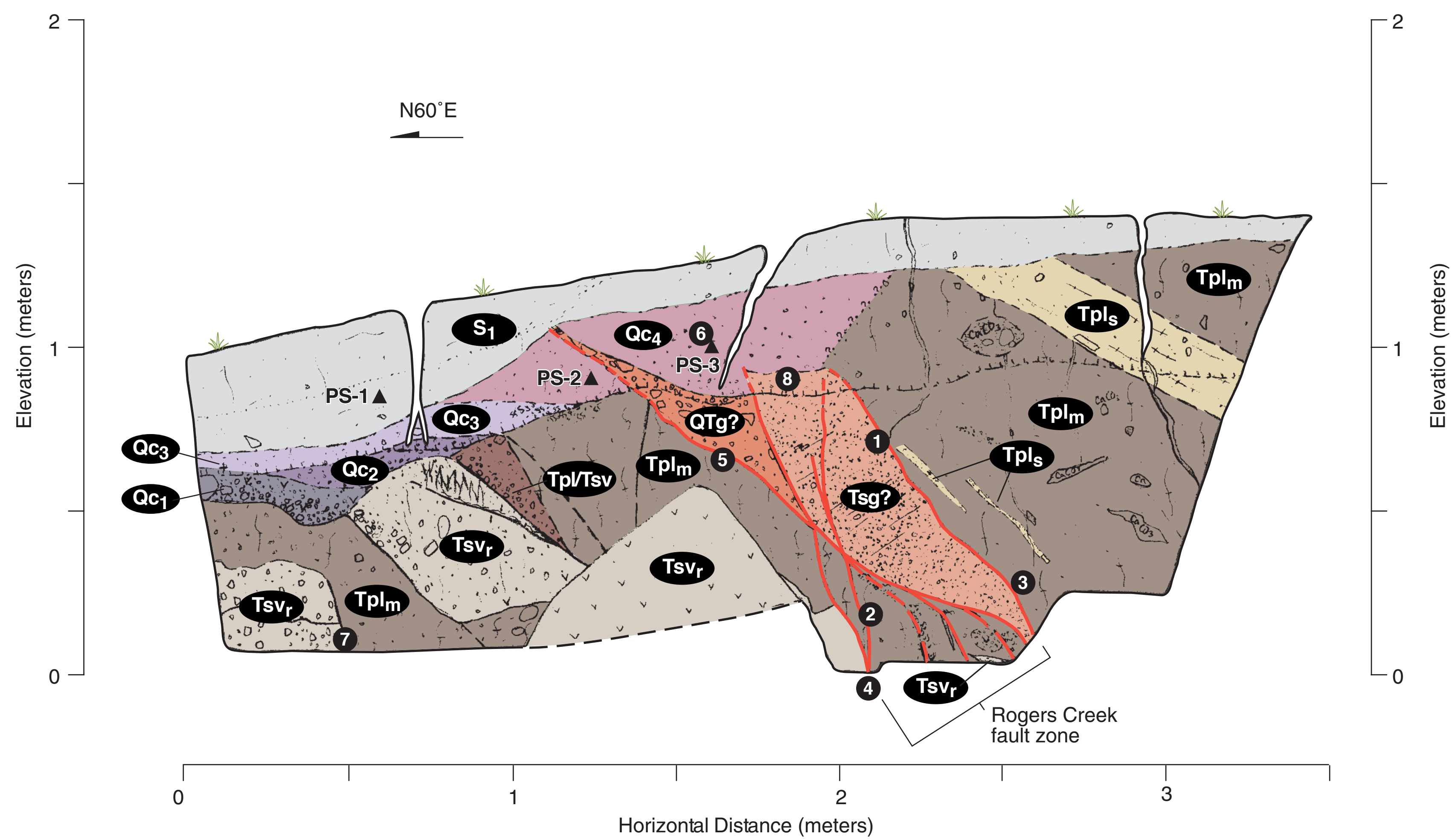
Symbols

- ? Fault; dashed where approximately located; queried where uncertain
- Spring
- T-1 Location and designation of trench
- Qt3 80.74 Basal strath elevation
- Thalweg of active stream channel

N

0 25 m

Figure 5. Quaternary geologic and geomorphic map of the Martinelli Ranch site showing the approximate locations of active traces of the Rodgers Creek fault and geologic exposures documented during the investigation.



Explanation

S_1	Modern soil A horizon developed in late Holocene to historic colluvial deposits
Qc_4, Qc_3, Qc_2, Qc_1	Holocene colluvium derived from bedrock
QTg?	Gravelly clay derived from Sonoma Volcanic bedrock, age unknown
Tsg?	Sandy gravel derived from Sonoma Volcanic bedrock, age unknown
Tpl/Tsv	Tectonically sheared bedrock including Tpl and Tsv
Tpl_s	Tertiary lower Petaluma Formation, sandstone facies
Tpl_m	Tertiary lower Petaluma Formation, mudstone facies
Tsv_r	Tertiary Sonoma Volcanic bedrock, tuffaceous unit

For detailed unit descriptions refer to Appendix A.

Notes

1. Fault attitude: N11E, 56W
2. Fault attitude: N8W, 68W
3. Fault attitudes: N19W, 53SW; N22W, 45SW
4. Fault attitude measured across trench: N30W, 58SW
5. Fault occurs in both walls and places Qtg over Qc4.
6. Scarp-derived colluvium (?); degraded fault scarp interpreted as the contact between lower Petaluma Formation and Qc4.
7. Fault attitude in bedrock: N78W, vertical
8. Soil infiltration to depth of 10cm within volcaniclastic gravel unit; highly weathered and disrupted zone

Symbols

Fault, dashed where approximate

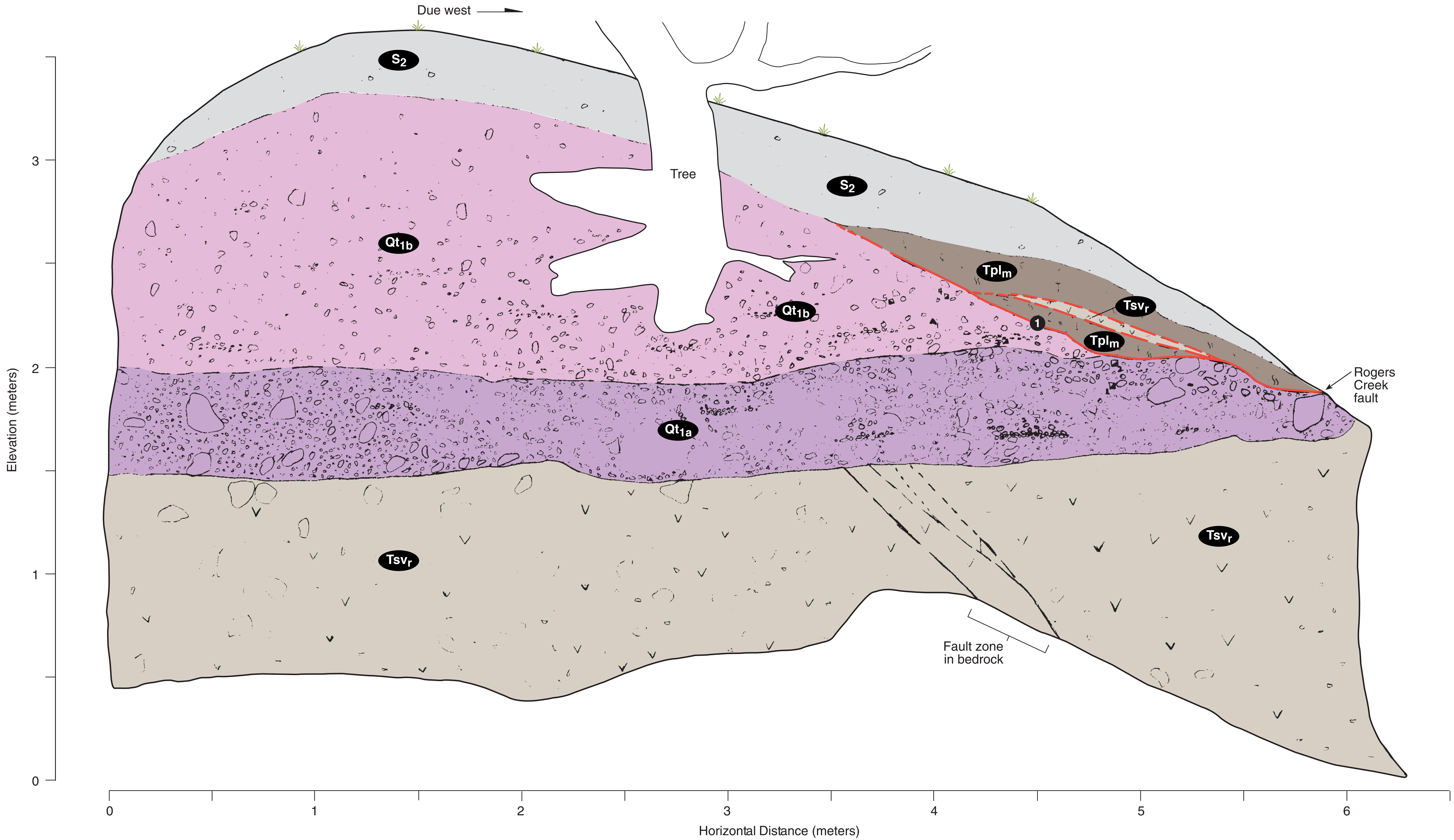
PS-1 ▲ Pollen sample

R O D G E R S   C R E E K

Trench T-1
Southeast Wall

WLA William Lettis & Associates, Inc. | Figure 6

1577 Rodgers Creek Fault



Explanation

S_2	Modern soil A horizon developed in late Holocene to historic colluvial deposits
Qt_{1b}, Qt_{1a}	Latest Pleistocene (?) to Holocene fluvial deposits of Qt_1
Tpl_m	Tertiary lower Petaluma Formation, mudstone facies
Tsv_r	Tertiary Sonoma Volcanic bedrock, tuffaceous unit

Note

1 Fault attitude: N6E, 23NW

Symbols

Fault, dashed where approximate

CaCO3

For detailed unit descriptions refer to Appendix A.

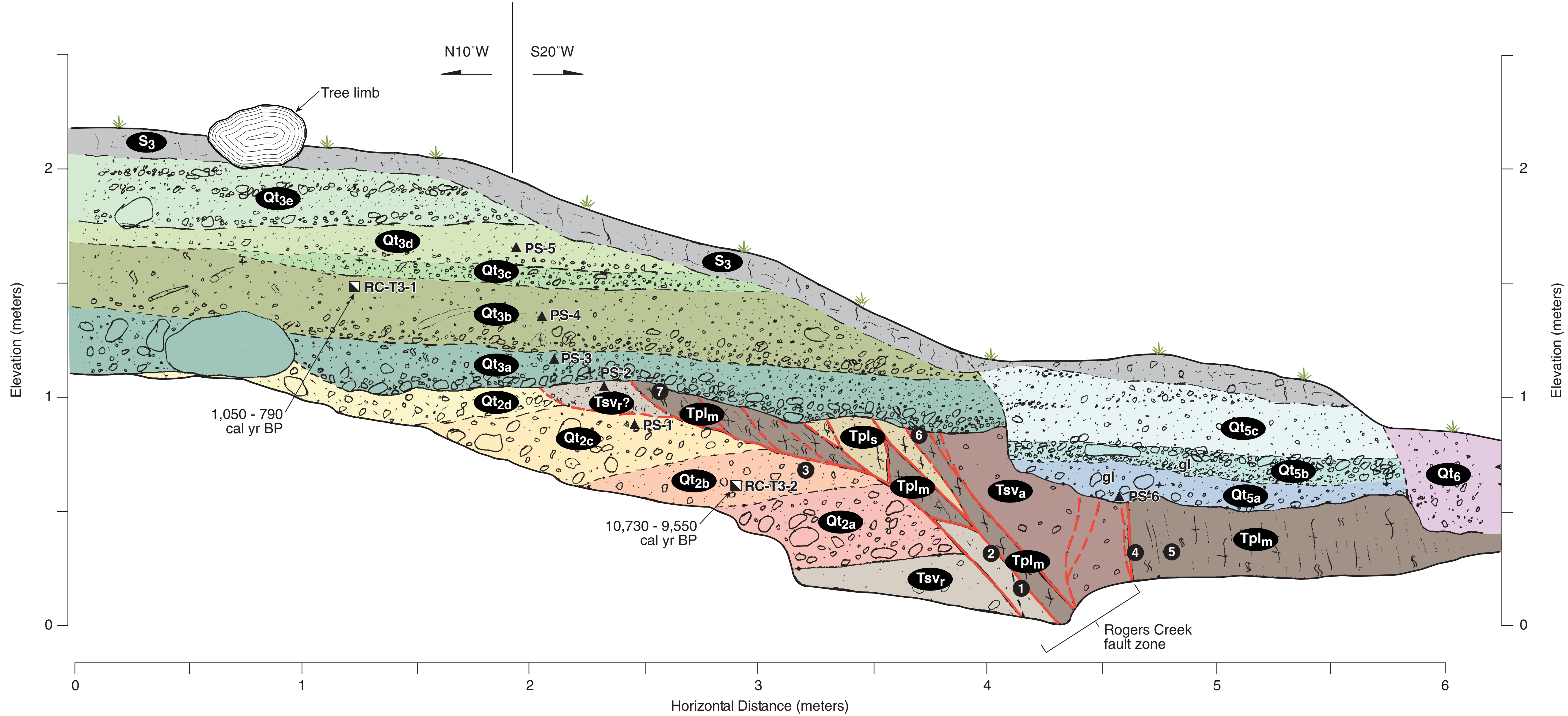
RODGERS CREEK

Trench T-2
South Wall of Creek Bank

WLA William Lettis & Associates, Inc.

Figure 7

1577 Rodgers Creek Fault



Explanation

- S_3 — Modern soil A horizon developed in late Holocene to historic alluvial/colluvial deposits
- Qt_6 — Historic point bar deposits
- Qt_{5c}, Qt_{5b}, Qt_{5a} — Historic fluvial deposits of Qt_5
- Qt_{3e}, Qt_{3d}, Qt_{3c}, Qt_{3b}, Qt_{3a} — Latest Holocene fluvial deposits of Qt_3
- Qt_{2d}, Qt_{2c}, Qt_{2b}, Qt_{2a} — Early Holocene fluvial deposits of buried Qt_2
- Tpl_s — Tertiary lower Petaluma Formation, sandstone facies
- Tpl_m — Tertiary lower Petaluma Formation, mudstone facies
- Tsv_r — Tertiary Sonoma Volcanic bedrock, tuffaceous unit
- Tsv_a — Tertiary Sonoma Volcanic bedrock, andesite unit

For detailed unit descriptions refer to Appendix A.

Notes

1. Fault attitude: N36W, 38W
2. Fault attitude: N36W, 43W
3. Fault attitude: N14E, 7N; N17E, 11N
4. Fault attitude: N32W; vertical
5. Attitudes of fractures and fabric in Tpl: N38W, 44N; N31W, 54N; N58W, 55N; N24W, 51N
6. Surveyed strath surface underlying Qt_3.
7. Surveyed strath surface underlying Qt_3.

Symbols

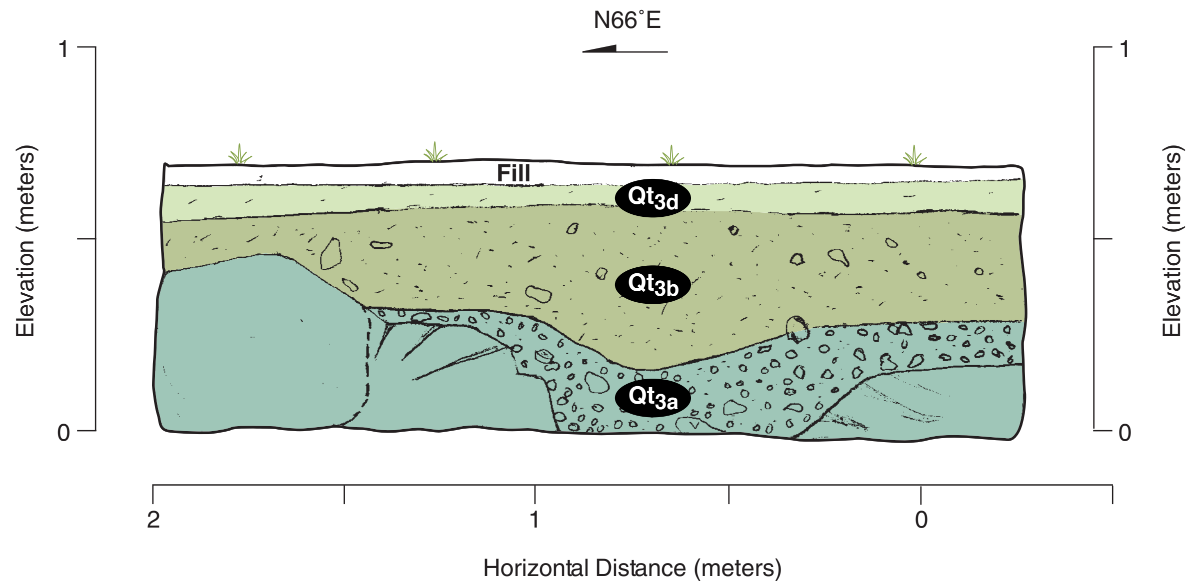
- Fault, dashed where approximate
- **PS-1** ▲ Pollen sample
- **RC-T3-2** ◪ Radiocarbon sample (detrital charcoal)
- **gl** Glass indicates historical deposit
- CaCO3

R O D G E R S C R E E K

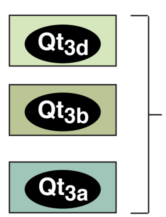
Trench T-3
South Wall

WLA William Lettis & Associates, Inc. | Figure 8

1577 Rodgers Creek Fault



Explanation



Latest Holocene to historic fluvial deposits of Qt3

For detailed unit descriptions refer to Appendix A.

RODGERS CREEK

Trench T-4
South Wall

WLA William Lettis & Associates, Inc. | Figure 9

1577 Rodgers Creek Fault

Photo 1. Panoramic view to the east showing the locations of creek and test pit exposures and active trace of the Rodgers Creek fault documented at the Martinelli Ranch site.

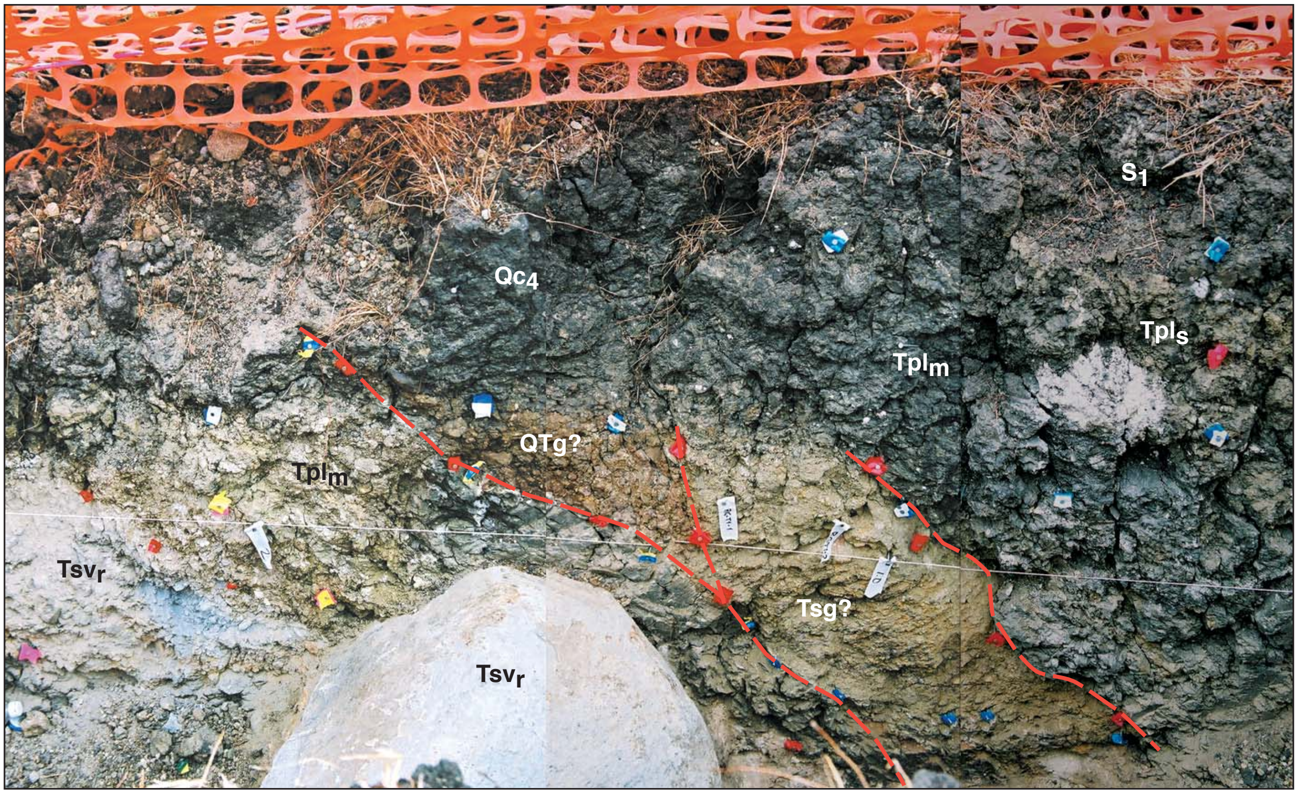


Photo 2. South wall of test pit T-1, showing active fault zone and cross-cutting relationships between bedrock and colluvium. Refer to Figure 6 and Appendix A for explanation of geologic units.

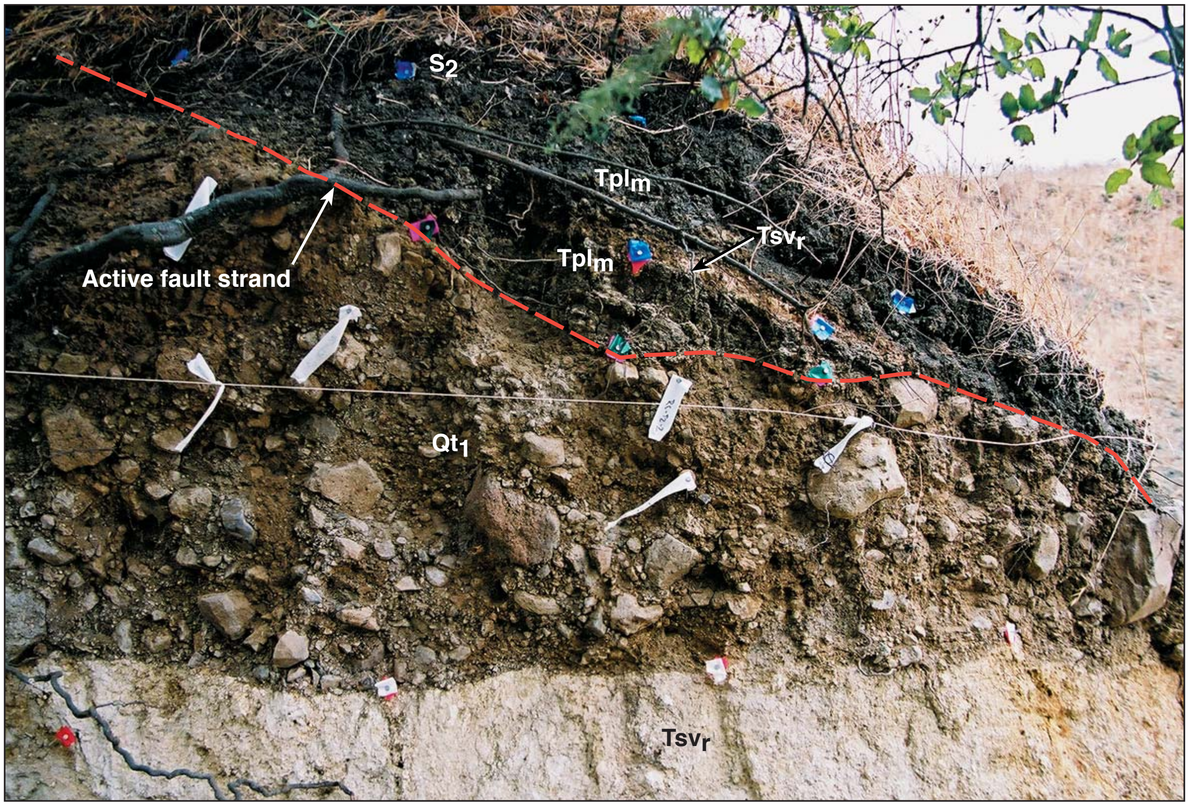


Photo 3. View to the south of creek exposure T-2 showing active fault strand that juxtaposes Tertiary lower Petaluma Formation against fluvial strata of terrace Qt_1. Refer to Figure 7 and Appendix A for explanation of geologic units.

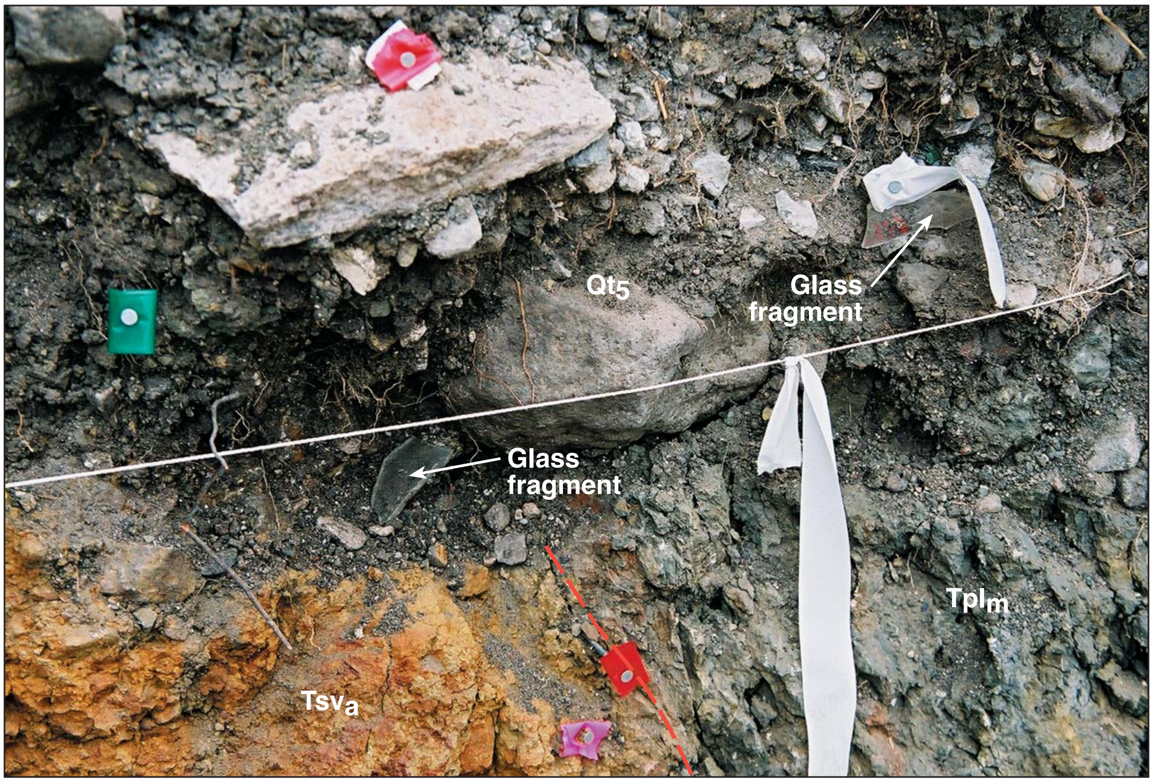


Photo 5. Close up of exposure T-3, showing historic terrace Qt5 containing glass fragments overlying faulted Tertiary lower Petaluma Formation (Tpl_m) and Sonoma Volcanics (Tsv_a).

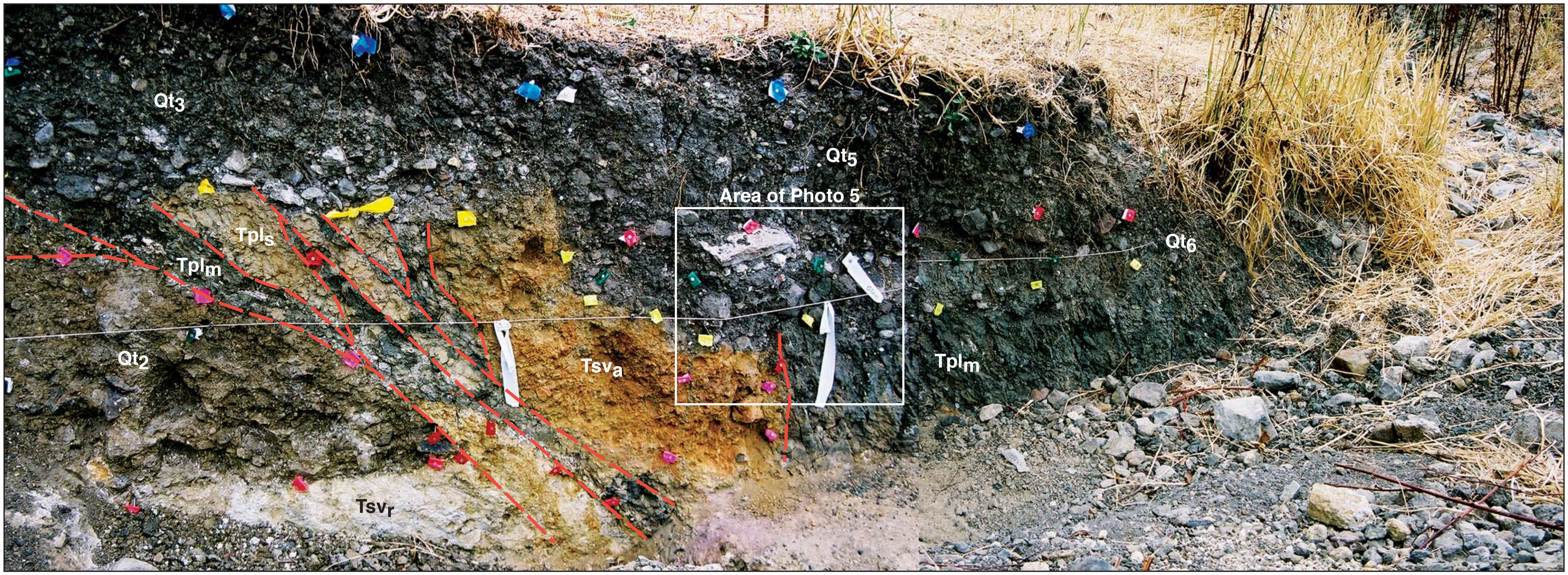


Photo 4. View to the southeast showing stratigraphic and structural relationships documented in creek exposure T-3. Active strands of the Rodgers Creek fault truncate fluvial deposits of Qt$_2$. Younger alluvial deposits (Qt$_3$, Qt$_5$, and Qt$_6$) are undeformed. Refer to Figure 8 and Appendix A for explanation of geologic units.

APPENDIX A—Detailed Geologic Unit Descriptions

$\boxed{S_1}$ $\boxed{S_2}$ $\boxed{S_3}$ – **Modern soil A horizon developed in late Holocene to historic alluvial/colluvial deposits.** Subunits are numbered according to trench exposure; numbers do not relate to relative ages of deposits. S_1—silty clay, gray to light gray (2.5Y 5/1), dry; occasional subrounded clasts, <0.5 cm in diameter, many roots; prominent large (5- to 10-cm wide) desiccation cracks. Unit thickens across fault toward east; lower contact is gradational and wavy to smooth. S_2—Silty clay with gravel, dark grayish brown (2.5Y 4/2), dry; poorly consolidated, weak pedogenic structure, porous, many fine rootlets and roots, matrix supported; clast lithology is volcanic, with occasional subangular to subrounded clasts; lower contact is gradational and wavy. S_3—silty clay, gray (2.5Y 5/1), dry; poorly consolidated, no pedogenic structure, porous, many fine rootlets and roots, matrix supported; lithology is volcanic, with occasional subangular to subrounded clasts; lower contact is gradational and wavy.

$\boxed{Qt_6}$ – **Historic point bar deposits.** Gravelly silt, gray (2.5Y 6/1), dry; fines upward, poorly bedded, many rootlets. Subrounded gravel ranges from 2 mm to 5 cm in diameter; lower contact is clear and smooth.

$\boxed{Qt_{5c}}$ – **Historic fluvial deposits of Qt_5.** Silty clay with gravel to a gravelly silt, gray (2.5Y 6/1), dry; texture fines upward, poorly bedded overall, many rootlets, slight angular to blocky pedogenic structure; clasts are subrounded, clast diameter ranges from 2 mm to 5 cm, with 1 cm average clast diameter; lower contact is clear and smooth.

$\boxed{Qt_{5b}}$ – **Historic fluvial deposits of Qt_5.** Gravel with sand and silt, gray (2.5Y 6/1), dry; poorly consolidated, many very fine rootlets, glass and debris within unit; lithology is volcanic, clasts are subrounded to subangular, clast size ranges from 2 mm to 20 cm, average 4 to 5 cm clast size; lower contact is wavy and clear to gradational.

$\boxed{Qt_{5a}}$ – **Historic fluvial deposits of Qt_5.** Clayey gravel with sand, gray (2.5Y6/1), dry; many very fine rootlets, poorly consolidated, no clear bedding, glass and historic debris within unit; clasts are subrounded, and range in diameter from 2 mm to 3 cm, 1 cm on average; lower contact is clear and wavy to smooth.

$\boxed{Qt_4}$ – **Latest Holocene to historic fluvial deposits of Qt_4.** Deposits associated with Qt4 were identified by detailed geologic mapping of the site (Figure 5) but were not encountered in the excavations.

$\boxed{Qt_{3e}}$ – **Latest Holocene fluvial deposits of Qt_3.** Gravel with silt and clay, dark gray (5Y 4/1), dry; poorly consolidated, many pores, many fine rootlets and some medium roots, moderately well bedded, some vertical desiccation cracks, matrix supported overall; clast lithology is volcanic, subangular clasts ranging in diameter from 2 mm to 10 cm; lower contact is clear and smooth.

$\boxed{Qt_{3d}}$ $\boxed{Qt_{3c}}$ – **Latest Holocene fluvial deposits of Qt_3.** Gravel with clay grading to gravelly silt with clay, dark gray (2.5Y 4/1), dry; matrix supported, no pedogenic structure, many pores, many fine roots, some vertical desiccation cracks. Deposit consists of two components that show a fining upward trend: Qt3d is gravelly silt with clay and represents the finer upper part of the deposit; Qt3c is predominantly gravel with clay. Clasts are subrounded, diameter ranges from 2 mm to 2 cm, 5 mm on average; lower contact is abrupt and smooth.

$\boxed{Qt_{3b}}$ – **Latest Holocene fluvial deposits of Qt_3.** Gravelly silt with clay, dark gray (5Y 4/1), dry; poorly to moderately bedded, common rootlets, few large roots, general fining upward trend, matrix supported; clast size ranges from 2 mm to 3 cm, 0.5 to 1 cm on average, minor clay films on base of clast, lithology is dominantly volcanic; lower contact is clear and smooth.

$\boxed{Qt_{3a}}$ – **Latest Holocene fluvial deposits of Qt_3.** Gravel, gray (2.5Y 5/1), dry; moderately consolidated, occasional distinct bedding, few rootlets, slight fining upward trend; subrounded clasts are predominantly volcanic and range in diameter from 5 mm to 8 cm, average 2 to 3 cm, minor discontinuous clay coatings on clasts; lower contact is abrupt and wavy to smooth.

$\boxed{Qt_{2d}}$ – **Early Holocene fluvial deposits of buried Qt_2.** Clayey gravel, yellowish brown (10YR 5/6), dry; trace $CaCO_3$; clast are angular, clay coated, 2 mm to 1 cm on average and have volcanic lithologies; lower contact is wavy and clear.

$\boxed{Qt_{2c}}$ – **Early Holocene fluvial deposits of buried Qt_2.** Gravel with clay and sand, brown (10YR 4/3), dry; 65% gravel, 15% clay, 10% sand, 10% silt; consolidated, tough, no clear bedding; lithology is dominantly volcanic, subrounded to subangular clasts, range in diameter from 2 mm to 4 cm, 1.5 cm on average; lower contact is smooth and gradational.

$\boxed{Qt_{2b}}$ – **Early Holocene fluvial deposits of buried Qt_2.** Clayey gravel, dark yellowish brown (10YR 4/4), dry; 45% gravel, 25% clay, 20% sand, 10% silt; few fine roots, no pores, consolidated; clast supported locally, clasts subangular to subrounded, range in diameter from 2 mm to 5 cm, 2 cm on average, lithology predominantly volcanic; lower contact is smooth and gradational.

$\boxed{Qt_{2a}}$ – **Early Holocene fluvial deposits of buried Qt_2.** Gravel, reddish brown (5YR 4/3), dry; 65% gravel, 25% clay, 10% sand; $CaCO_3$ veinlets, poorly bedded, well consolidated; dominantly clast supported, subangular clasts to moderately subrounded, lithology is typically mixed volcanics, range in size from 5 mm to 10 cm, discontinuous to continuous clay coatings on clasts; lower contact is abrupt and smooth with Tsv.

$\boxed{Qc_4}$ $\boxed{Qc_3}$ $\boxed{Qc_2}$ $\boxed{Qc_1}$ – **Holocene colluvium derived from bedrock.** Subunits numbered from oldest (Qc_1) to youngest (Qc_4). Qc_4— dark gray (2.5Y 4/1) clay with sand; occasional clasts, subrounded, massive, faulted against gravelly clay, unit QTg. Possible colluvial wedge derived from lower Petaluma Formation to the west. Qc_3—very dark grey (5Y 3/1) clay with olive (5Y 5/4) mottling derived from lower Petaluma Formation mudstone (Tpl_m). Qc_2—very dark grey (5Y 3/1) gravelly clay with pale olive (5Y 6/3) mottles. 25 to 35% subangular to subrounded clasts up to 3 cm in diameter. Clast lithology predominantly volcanic with minor mudstone clasts. Colluvium derived from sheared bedrock (Tpl/Tsv). Qc_1—yellowish brown (2.5Y 7/6) clast supported gravel derived from Sonoma Volcanic bedrock (Tsv_r).

$\boxed{Qt_{1b}}$ – **Latest Pleistocene (?) to Early Holocene fine-grained fluvial deposits of Qt_1.** Gravelly silt with sand, yellowish brown (10YR 5/4), dry; few roots, moderately consolidated, no pedogenic structure visible, weakly bedded, but generally massive, general fining upward trend; clasts are subrounded and have a volcanic lithology, range in diameter from 2 mm to 5 cm; lower contact is clear and smooth.

$\boxed{Qt_{1a}}$ – **Latest Pleistocene (?) to Early Holocene coarse-grained fluvial deposits of Qt_1.** Gravel with clay and sand, brown (10YR 4/3), dry; moderately to well consolidated; minor rootlets, clast supported; clast lithology is predominantly volcanic, clasts are subangular to subrounded, minor localized bedding visible, clast diameter ranges from 2 mm to 20 cm, with 2 to 3 cm on average; lower contact is abrupt and smooth.

$\boxed{QTg?}$ – **Gravelly clay derived from Sonoma Volcanic bedrock.** Gravelly clay with sand, dark reddish brown (5YR 3/3) moist, yellowish brown (10YR 5/4) dry; moderately hard, matrix supported, massive; clasts are subangular to subrounded, up to 6 cm in diameter, average size 1 cm; slight imbrication of clasts along eastern fault contact.

$\boxed{\text{Tsg?}}$ – **Sandy gravel derived from Sonoma Volcanic bedrock.** Sandy gravel, light yellowish brown (2.5Y 6/4); moderately hard to hard, well cemented. Very poorly sorted, mixed texture consisting of 15 to 60% gravel, 35 to 85% sand and minor (<5%) silt. Volcanic clasts up to 2 cm in diameter are subrounded to angular, and dominantly andesite. $CaCO_3$ coats some clasts and occurs in matrix; manganese nodules abundant. Unit is bounded by faults.

$\boxed{\text{Tpl/Tsv}}$ – **Tectonically sheared bedrock including Tpl and Tsv.** Alternating bands of both rhyolitic tuff, and mudstone with $CaCO_3$ nodules. Highly sheared along contacts between different lithologic units, moderately consolidated, floury.

$\boxed{\text{Tpl}_s}$ $\boxed{\text{Tpl}_m}$ – **Tertiary lower Petaluma Formation.** Mudstone with sandstone lenses, blue-gray (5Y 4/1); friable, some fine roots, weak bedding visible dipping westward in trench T-1, $CaCO_3$ nodules common, subparallel shear fabric typical, well consolidated; soil development to a depth of 0.5 m in trench T-1. Tpl_s represents sandstone facies; Tpl_m represents mudstone facies.

$\boxed{\text{Tsv}_r}$ – **Tertiary Sonoma Volcanic bedrock, tuffaceous unit.** Rhyolite tuff, white to yellowish tan (5Y 8/2); floury to granular, contains large, subrounded volcanic clasts, occasional iron stained zones, well consolidated, no visible structure.

$\boxed{\text{Tsv}_a}$ – **Tertiary Sonoma Volcanic bedrock, andesite unit.** Andesite, moderately to highly weathered, yellowish brown (10YR 5/6); clast supported where brecciated, iron staining on rock surfaces, subangular breccia clasts, range up to 8 cm long, very hard, in fault contact with Tpl.